CONTENTS

	Pages
Introduction	1
The Model	2
Heat Exchangers	2
Test Procedure	3
Conditions Tested	5
Results	6
Discussion of Results	8
TABLES 1 and 2	
PLATES 1 to 12	

Model Study of Narragansett Bay Effects of Fox Point Barrier on Cooling Water Temperatures

Interim Report 3

Introduction

1. Construction of a barrier across the Providence River in the vicinity of Fox Point was recently authorized by Congress. When completed, this barrier will protect a large portion of downtown Providence, Rhode Island, from flooding by extreme tides associated with tropical hurricanes which strike the New England Coast in the vicinity of Narragansett Bay. The Narragansett Electric Company operates two power generating stations which draw condenser cooling water from the Providence River, and the intake and outlet works for these plants are located upstream from the barrier site. The problem area is shown on plate 1, and the locations of the barrier and the intake and outlet works for cooling water are shown on plate 2.

2. The barrier will be equipped with sluice gates of adequate size and design to maintain the existing tidal prism upstream from the barrier site, but it was considered possible that changes in current patterns and vertical mixing caused by the barrier might result in increases in water temperature upstream from the structure and especially at the cooling water intakes. The tests reported herein were conducted to determine the effects of the barrier on water temperatures for average conditions of tide and fresh-water discharge. No attempt was made to determine the extreme seasonal fluctuations in water temperature, either without or

with the barrier installed in the model, since it was recognized that other provisions would have to be made for the intake of cooling water if the results of tests for average conditions indicated a significant increase in water temperature.

The Model

3. The tests were conducted in the comprehensive model of Narragansett Bay. A description of the model, as well as the details of its adjustment and verification, are presented in interim reports of February 1957 and June 1959 and are not repeated in this report. Since the model is designed and operated in accordance with the Froudian scale relationships, a temperature scale of 1:1 was applicable for the tests.

Test Technique

4. Water temperature in an area such as the Providence River is affected by many factors other than the circulation of cooling water, the most important of which are probably the air-water temperature difference and evaporation. Since these latter two factors could not be reproduced in a quantitative manner in the existing model, and since only the effects of the cooling water circulation were to be studied, it was necessary to develop a technique whereby the effects of cooling water circulation could be isolated by holding all other factors constant.

5. During the course of some exploratory tests, in which the circulation of cooling water was not simulated in the model, it was noted that the temperature of the model water varied by as much as $3^{\circ}F$ over the period of time considered to be necessary for the subsequent temperature tests. It was therefore obvious that some means for adjusting out the

effects of hourly and daily temperature differences would have to be devised so that the effects of cooling water circulation during the course of a test, and also from test to test, could be isolated. A correlation between the rate of change in air temperature and water temperature was first attempted, but it was soon found that short term changes in the rate of evaporation of the model water, which in turn affected the model water temperature, made such a correlation impossible.

6. From water temperature measurements made throughout the model during the exploratory tests, it was noted that a constant relationship existed between temperatures throughout the Providence River problem area of the model and that of the fresh water discharged into the Woonasquatucket and Seekonk Rivers. The factors which resulted in short term changes in water temperature throughout the model produced equal changes in the temperature of the fresh water, and since the circulation of cooling water could not affect in any way the temperature of the fresh water, it was decided that the fresh water temperature would serve as a satisfactory basis for adjusting out all effects other than those attributable to cooling water circulation. All temperature data presented in this report are therefore expressed in terms of differences, either plus or minus, from the temperature of the fresh water.

Test Procedure

7. A mean tide range of 3.6 ft at Newport was reproduced for all tests, and the salinity of the model ocean was maintained at 33.0 parts per thousand. Average fresh-water discharges were reproduced in all major tributaries; these discharges were 700 cfs in the Pawtuxet River,

400 cfs in the Woonasquatucket and Moshasuck Rivers combined, 1500 cfs in the Seekonk River, and 1400 cfs in the Taunton River. The model was operated for 30 tidal cycles before circulation of cooling water was undertaken to insure that salinity conditions were stable when circulation was started. To simulate the effects of circulation of cooling water, the proper volumes of water were pumped from the model at the respective intake locations and depths, heated to effect the average temperature increase observed in the prototype, then returned to the model at the respective outfall locations and depths. In each test, operation was continued until periodic measurements showed that no further changes in temperature were taking place, and temperatures throughout the problem area were stable for the conditions of the test.

8. In the prototype, cooling water for the Manchester Street generating station is obtained through one intake and discharged through two outfalls, while that at the South Street station is obtained through two intakes and discharged through one outfall. In the model, one intake and one outfall were provided for each generating station as indicated on plate 2. The intakes and outfalls were positioned at the proper depths so that cooling water was drawn from and released into the same strata in both model and prototype.

9. Thermometers were installed in both intake lines, and the minimum and maximum temperatures were observed during each tidal cycle after beginning circulation of cooling water. The minimum and maximum values were averaged to obtain an approximation of the mean temperature,

which was used as a basis for adjusting the temperatures of two hot water baths through which the intake water passed in a coil before being returned to the river. The hot water baths were adjusted to effect a 10°F rise over intake temperature for the Manchester Street station and a 15°F rise over intake temperature for the South Street station. The quantities circulated were 455 cfs for the Manchester Street station and 440 cfs for the South Street station. All tests were continued for 50 tidal cycles after beginning the circulation of cooling water, even though temperatures were essentially stable at all observation stations after about 30 tidal cycles.

10. In addition to temperature measurements in the intakes, maximum and minimum temperatures at surface and bottom were measured at stations B and G (plate 2) at intervals of 5 tidal cycles throughout each test. Running plots of these measurements and those in the intakes were maintained as an index to the time of temperature stability in the problem area. The temperature of the fresh water was measured at close intervals for reference purposes. Near the end of each test, when it was certain that temperatures were stable throughout the area, temperatures were measured at half-hourly intervals over a complete tidal cycle in both intakes, at the surface above both intake locations, and at surface and bottom at stations A, B, G, and 19 (plate 2). On completion of tidal cycle 50, blocks shaped to fit the channel were inserted at the two locations shown on plate 2 at the time of high water slack of the current at the barrier site, the circulation of cooling water was stopped, the water between the blocks was mixed quickly and thoroughly, and an average temperature measurement for the entire area was obtained. It was

considered that this latter procedure would provide an absolute measure of the effects of the barrier on the average water temperature upstream from the structure, whereas values derived by averaging point measurements at a number of locations might not yield an absolute value.

Conditions Tested

11. The three conditions tested in the model were the existing condition, referred to hereinafter as the base test, and plans 1 and 2. Both plans incorporated three 40-ft-wide sluice gates, having sill elevations of -15.0 ft MSL. For plan 1, the sluice gates were located near the east bank of the river (plate 2), while for plan 2 the gates were located to the west of the center of the river. Operating conditions for the three tests were identical and in accordance with the following tabulation:

Generating Sta	Intake Sill Elev*	Intake Height in Ft	Outfall Sill Elev*	Outfall Height in Ft.	Circulation cfs	Temp. Rise ^{o}F
South St.	-25.5	12.0	-12.0	10.0	440	15
Manchester St.	-15.0	7.5	- 4.5	7.0	455	10

*Elevations are in ft below MSL. Locations of intakes and outfalls are shown on plate 2.

Results

12. The results of the tests are presented in tables 1 and 2 and on plates 3-12. Plates 3-6 show the results of periodic measurements of maximum and minimum temperatures in the two intakes and at surface and bottom at stations B and G for the duration of the base test and the two plan tests. As described in paragraph 6, temperatures for both the base test and the plan tests are expressed as differences from the

fresh-water temperature; therefore, the temperature differences between base test and plan indicate directly the effects of the plan on temperatures at the point of measurement. At the South Street intake (plate 3), plan 1 caused an increase in maximum temperature of about 2.5°F at the time of stability, while the minimum temperature was increased about 1.5°F. At this location, plan 2 caused an increase in maximum temperature of about 1.5°F, while the minimum temperature was not changed appreciably.

13. At the Manchester Street intake (plate 4), both plans 1 and 2 caused significant increases in maximum and minimum temperatures. The increase in maximum temperature for plan 1 was about 5.0°F and that for plan 2 was about 7.0°F, while the increase in minimum temperature for both plan 1 and plan 2 was about 6.0°F. Increases in maximum and minimum temperatures at surface and bottom were also observed at stations B and G for both plans (plates 5 and 6); the increases ranged from about 0.5°F to about 7.0°F.

14. Plates 7 and 8 show the effects of plans 1 and 2 on temperatures throughout a tidal cycle, after stability had been attained, at the South Street and Manchester Street intakes, respectively. Plates 9-12 present similar data for surface and bottom for stations A, B, G, and 19, respectively. Data presented on these plates indicate that, in some instances (Station A bottom, for example), the average temperature was increased more than was the maximum or the minimum temperature.

15. The effects of both plans on maximum and minimum temperatures at all observation stations are summarized in table 1, and the effects on average temperature over a tidal cycle at the time of stability are summarized in table 2. At the bottom of table 2, the measurements

obtained after thorough mixing the water in the problem area (described in paragraph 10) are presented. These latter measurements are considered to be a reliable index to the effects of the two plans on the average water temperature in the problem area, and it will be noted that increases of 3.0°F for plan 1 and 3.4°F for plan 2 were indicated.

Discussion of Results

16. The results of the model tests indicate that the Fox Point barrier would reduce circulation between that portion of the Providence River downstream from the structure and that upstream where the cooling water intakes and outlets are located, and the reduced circulation would cause an increase in the average water temperature of the upstream area by 3.0°F to 3.5°F. The model tests indicate that the temperature of the intake water at the South Street station would be increased by less than the average and that at the Manchester Street station would be increased by more than the average. This difference is attributed to the fact that the South Street intake is appreciably deeper than the Manchester Street intake; therefore, the effects of the reduced circulation are not so great.

17. The tests also indicate that the reduced circulation would cause a slight reduction in water temperature downstream from the barrier, as evidenced by temperature measurements at station 19. It therefore follows that any scheme for drawing cooling water from the downstream area would provide cooler water to the plants with the barrier installed than without the structure.

18. While not entirely pertinent to the purpose of the model tests, data obtained during the exploratory tests and the base tests indicate that the present circulation of cooling water has a major effect on water

temperatures throughout the problem area. During the exploratory tests, which did not simulate circulation of cooling water, it was found that the average water temperature in the problem area was $1.0^{\circ}F$ less than the fresh-water temperature. In the base test, which simulated the existing circulation, the average temperature was $4.2^{\circ}F$ above the fresh-water temperature, or an increase in average temperature of about $5.2^{\circ}F$ because of present circulation.

TABLE 1

EFFECT OF FOX POINT BARRIERS ON TEMPERATURE EXTREMES

Location		Temperature Differences in Degrees Fahrenheit				
		Base Test*	Plan 1*	Effect of Plan 1	Plan 2*	Effect of Plan 2
South St. Intake	Max.	-0.5	1.9	2.4	1.3	1.8
	Min.	-0.5	1.0	1.5	- 0.2	0.3
Manchester St. Intake	Max.	8.8	14.1	5.3	15.9	7.1
	Min.	-0.5	5.4	5.9	5.8	6.3
Station B-Surface	Max.	10.8	17.2	6.4	17.7	6.9
	Min.	2.0	3.6	1.6	3.8	1.8
Station B-Bottom	Max.	-0.8	2.0	2.8	1.8	2.6
	Min.	-1.2	0.2	1.4	-0.7	0.5
Station G-Surface	Max.	8.0	9.7	1.7	10.3	2.3
	Min.	1.0	1.8	0.8	1.4	0.4
Station G-Bottom	Max.	9.0	12.5	3.5	11.0	2.0
	Min.	4.0	6.2	2.2	6.2	2.2
Station A-Surface	Max.	11.1	10.5	-0.6	12.5	1.4
	Min.	2.8	2.5	-0.3	2.6	-0.2
Station A-Bottom	Max.	8.3	9.8	1.5	10.6	2.3
	Min.	-0.2	2.4	2.6	4.9	5.1
Station 19-Surface	Max.	11.1	9.3	-1.8	10.4	-0.7
	Min.	1.9	2.2	0.3	2.4	0.5
Station 19-Bottom	Max.	-1.0	-0.8	0.2	-1.9	-0.9
	Min.	-1.2	-0.9	0.3	-2.8	-1.6

NOTE: *Values are differences between the temperature extremes at the observation points at time of stability and the fresh-water temperature. Tabulated values are averages of two identical tests.

TABLE 2

EFFECT OF FOX POINT BARRIERS ON AVERAGE WATER TEMPERATURES THROUGHOUT A TIDAL CYCLE

		Temperature Differences in Degrees Fahrenheit				
		Base Test	Plan 1 Barrier Installed		Plan 2 Barrier Installed	
Location	Depth	Temperature Difference*	Temperature Difference*	Effect of Plan 1	Temperature Difference*	Effect of Plan 2
Manchester St. Intake	Surface	6.8	8.4	1.6	11.9	5.1
	Intake	2.1	10.0	7.9	10.6	8.5
South St. Intake	Surface	5.6	8.1	2.5	9.4	3.8
	Intake	-0.5	1.9	2.4	0.7	1.2
Station A	Surface	6.9	6.4	-0.5	8.2	1.3
	Bottom	1.8	6.6	4.8	8.0	6.2
Station B	Surface	7.8	11.3	3.5	12.7	4.9
	Bottom	-0.8	1.4	2.2	0.6	1.4
Station G	Surface	3.8	5.4	1.6	5.2	1.4
	Bottom	6.8	9.7	2.9	9.8	3.0
Station 19	Surface	7.1	6.1	-1.0	6.5	-0.6
	Bottom	-1.1	-0.8	0.3	-2.4	-1.3
Entire area (after mixing at end of test)		4.2	7.2	3.0	7.6	3.4

NOTE: *Values are differences between the average temperature over a tidal cycle at the observation point and the fresh-water temperature. Tabulated values are averages of two identical tests.

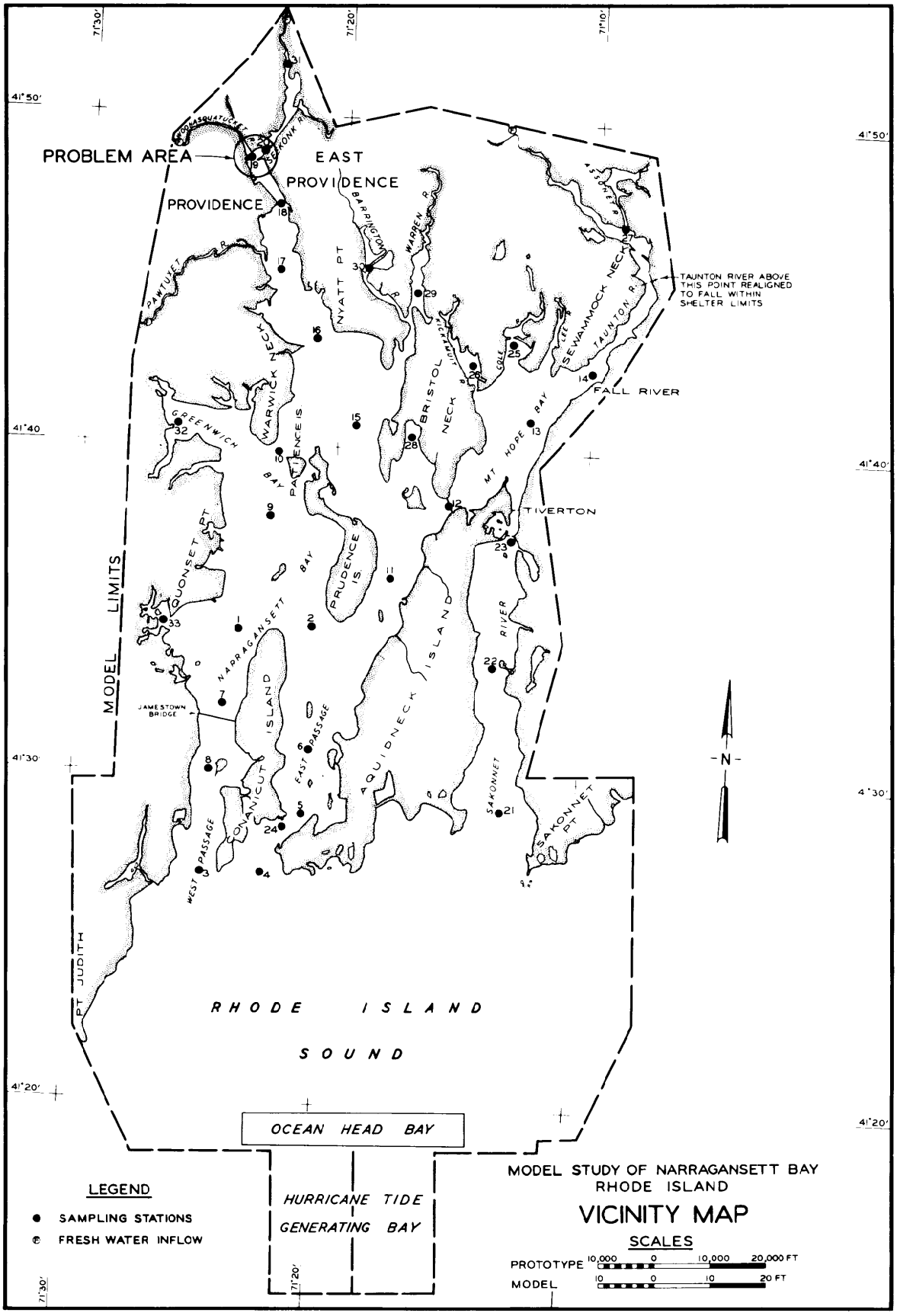

PROBLEM AREA
EAST PROVIDENCE
PROVIDENCE
PAWTUCKET
SEEKONK R.
BARRINGTON
WARREN R.
ASSONET R.
TAUNTON R.
TAUNTON RIVER ABOVE THIS POINT REALIGNED TO FALL WITHIN SHELTER LIMITS
SEWAMMOCK NECK
FALL RIVER
GREENWICH BAY
WARWICK NECK
PATIENCE IS
BRISTOL NECK
MT HOPE BAY
TIVERTON
QUONSET PT
PRUDENCE IS
NARRAGANSETT BAY
MODEL LIMITS
JAMESTOWN BRIDGE
CONANICUT ISLAND
EAST PASSAGE
AQUIDNECK ISLAND
SAKONNET RIVER
SAKONNET PT
WEST PASSAGE
PT JUDITH
RHODE ISLAND SOUND
OCEAN HEAD BAY
HURRICANE TIDE GENERATING BAY
41°50'
41°40'
41°30'
41°20'
71°30'
71°20'
71°10'
LEGEND
SAMPLING STATIONS
FRESH WATER INFLOW
N
MODEL STUDY OF NARRAGANSETT BAY
RHODE ISLAND
VICINITY MAP
SCALES
PROTOTYPE 10,000 0 10,000 20,000 FT
MODEL 10 0 10 20 FT

Plate 1

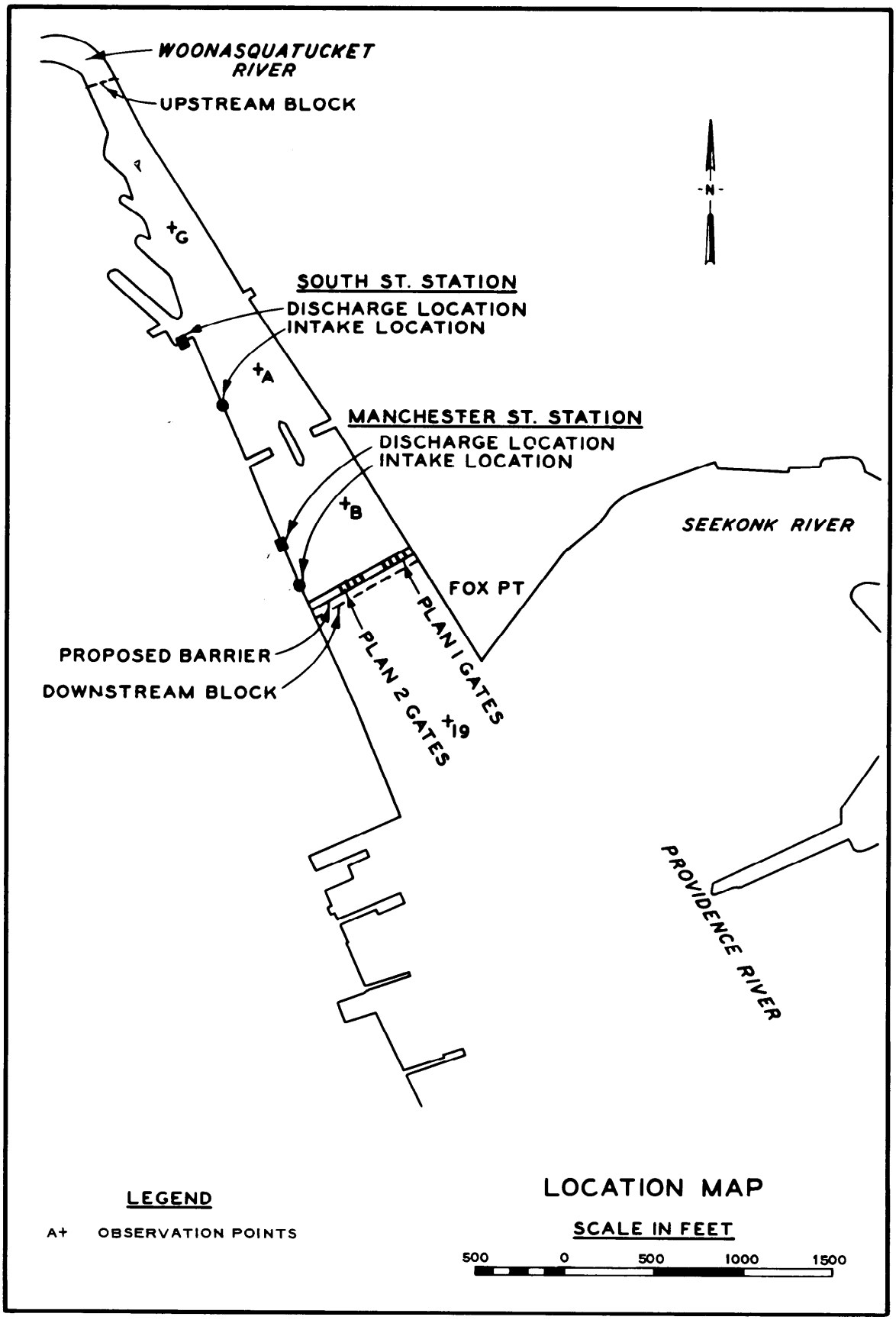

WOONASQUATUCKET RIVER
UPSTREAM BLOCK
+G
SOUTH ST. STATION
DISCHARGE LOCATION
INTAKE LOCATION
+A
MANCHESTER ST. STATION
DISCHARGE LOCATION
INTAKE LOCATION
+B
SEEKONK RIVER
FOX PT
PLAN I GATES
PLAN 2 GATES
+19
PROPOSED BARRIER
DOWNSTREAM BLOCK
PROVIDENCE RIVER
N
LEGEND
A+ OBSERVATION POINTS
LOCATION MAP
SCALE IN FEET
500 0 500 1000 1500

Plate 2

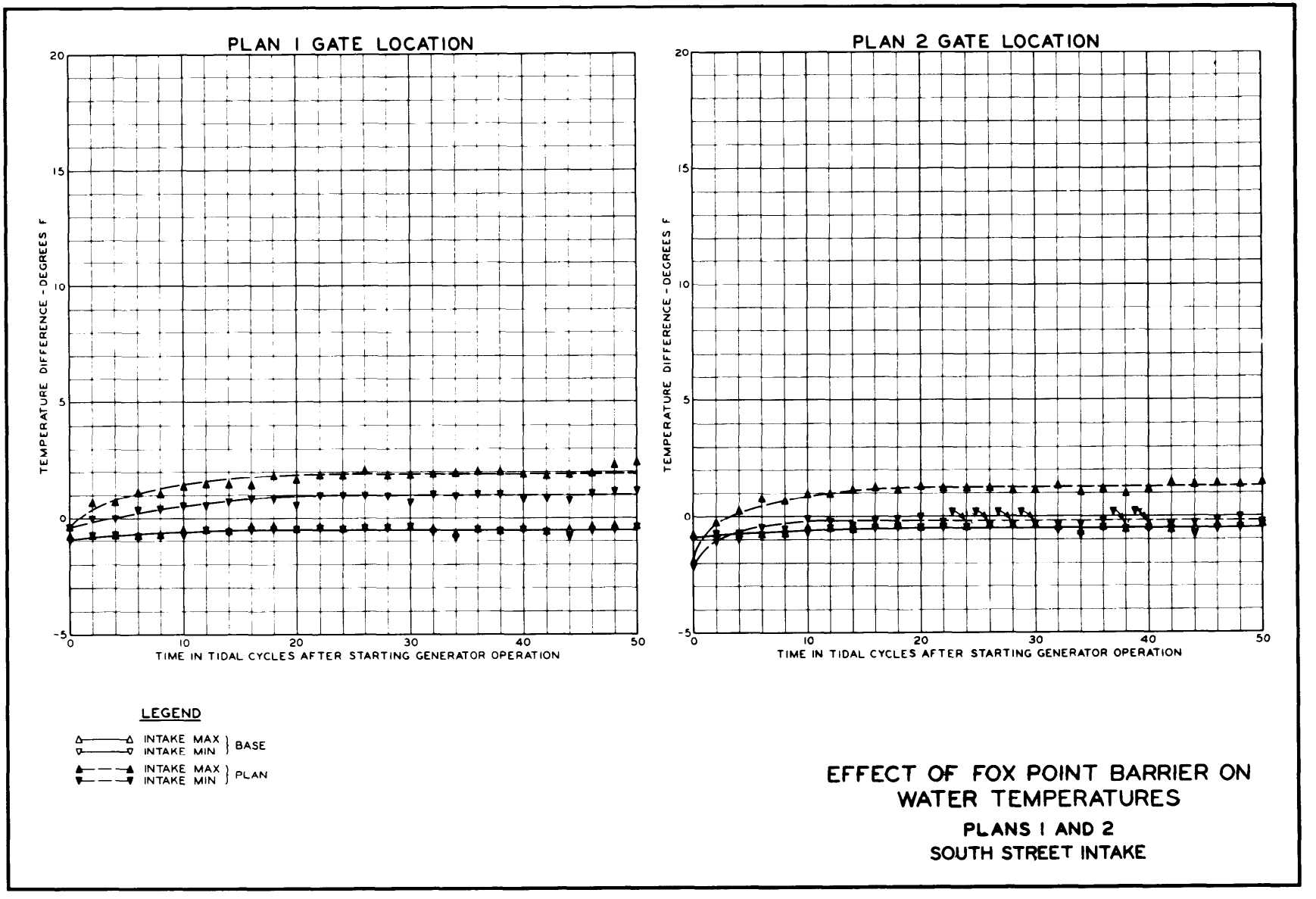
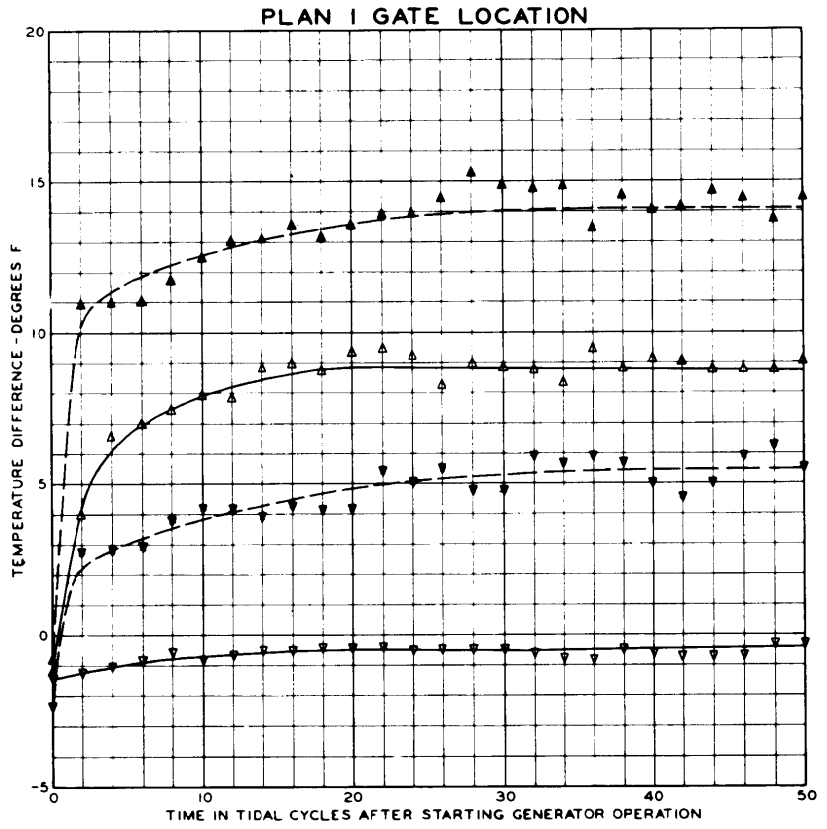
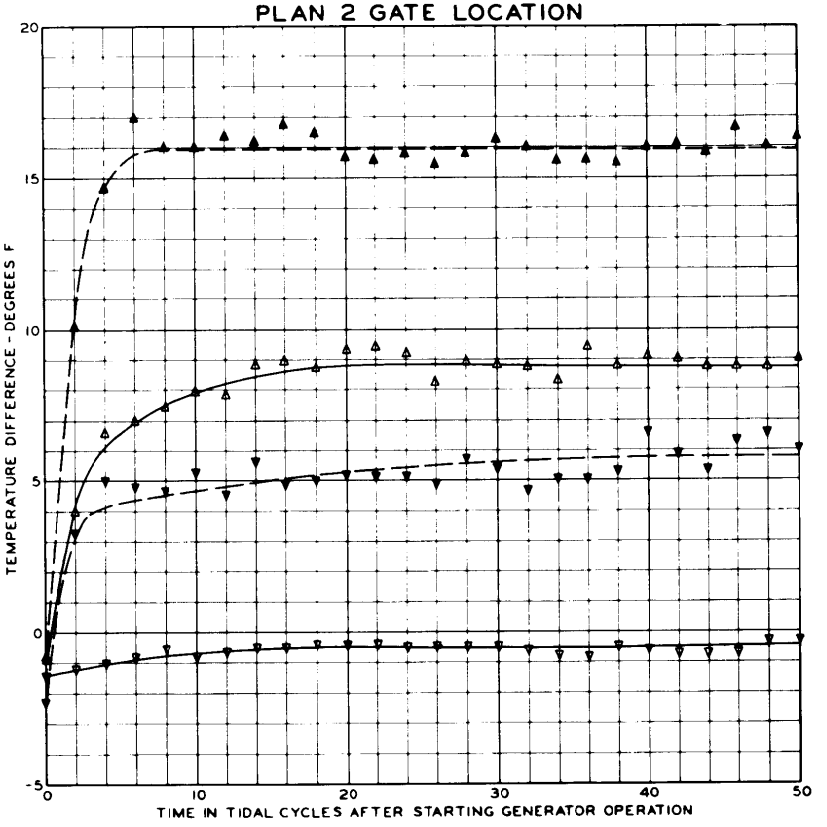

PLAN 1 GATE LOCATION
PLAN 2 GATE LOCATION
TEMPERATURE DIFFERENCE - DEGREES F
TIME IN TIDAL CYCLES AFTER STARTING GENERATOR OPERATION
20
15
10
5
0
-5
0
10
20
30
40
50
LEGEND
INTAKE MAX
INTAKE MIN
BASE
INTAKE MAX
INTAKE MIN
PLAN
EFFECT OF FOX POINT BARRIER ON
WATER TEMPERATURES
PLANS 1 AND 2
SOUTH STREET INTAKE

Plate 3





LEGEND

INTAKE MAX } BASE
INTAKE MIN }

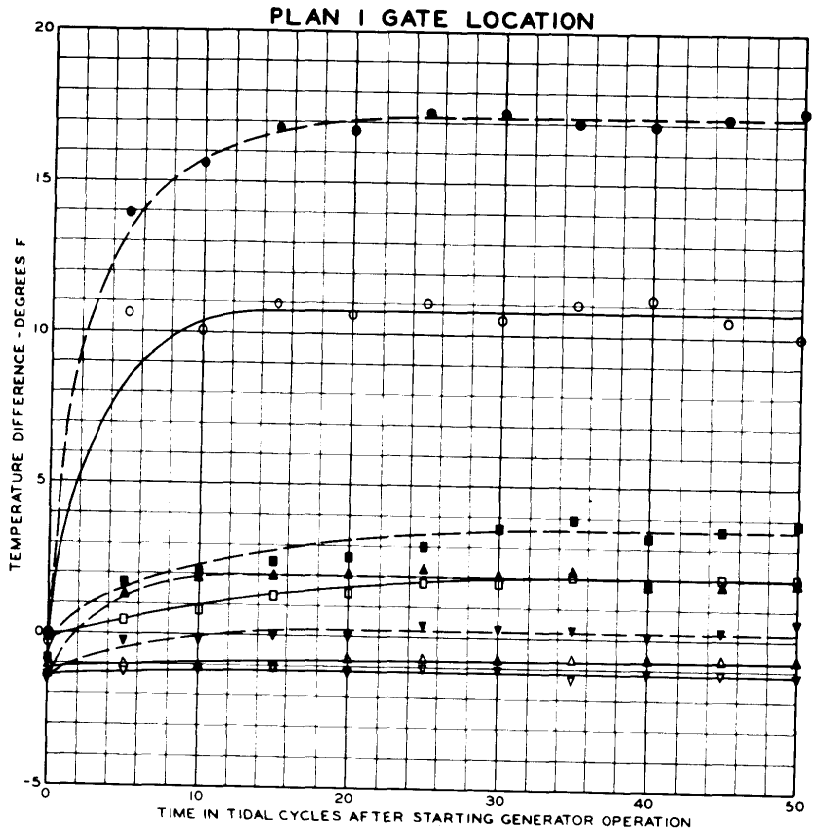
INTAKE MAX } PLAN
INTAKE MIN }

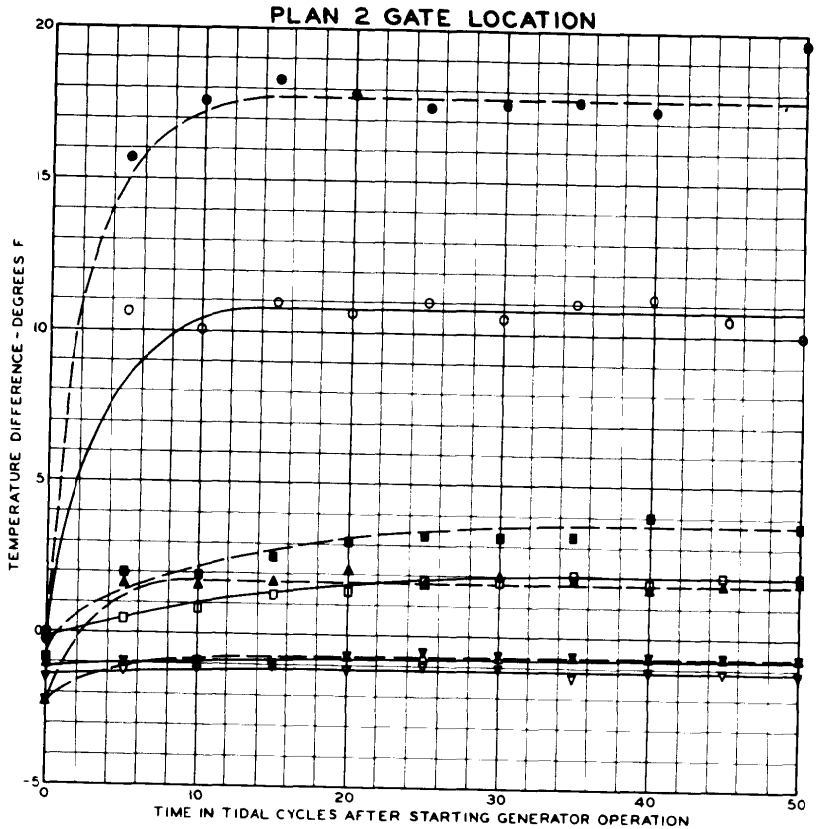
EFFECT OF FOX POINT BARRIER ON WATER TEMPERATURES

PLANS 1 AND 2

MANCHESTER STREET INTAKE

Plate 4





LEGEND

- SURFACE MAX
- SURFACE MIN
- BOTTOM MAX
- BOTTOM MIN

} BASE

- SURFACE MAX
- SURFACE MIN
- BOTTOM MAX
- BOTTOM MIN

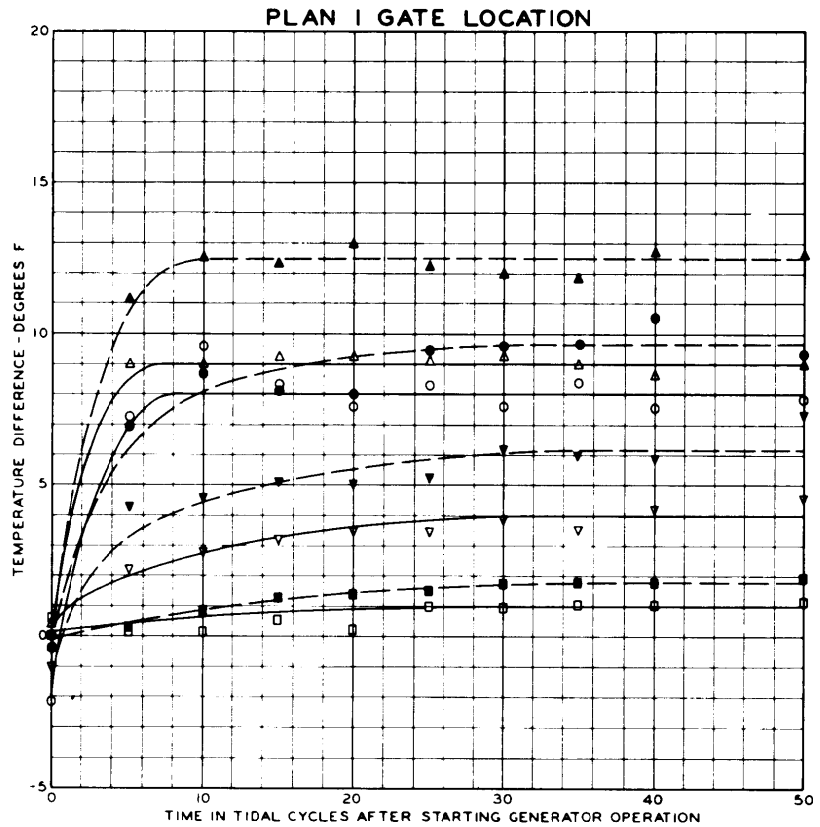
} PLAN

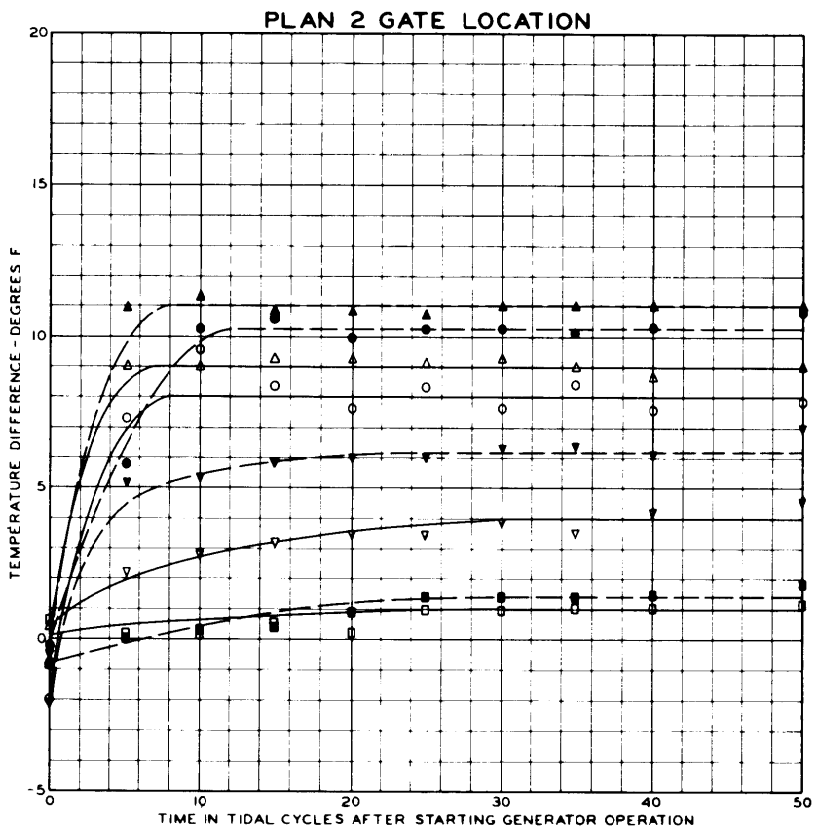
EFFECT OF FOX POINT BARRIER ON WATER TEMPERATURES

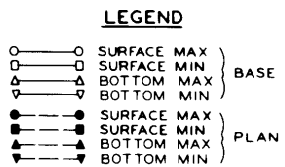
PLANS 1 AND 2

STATION B

Plate 5





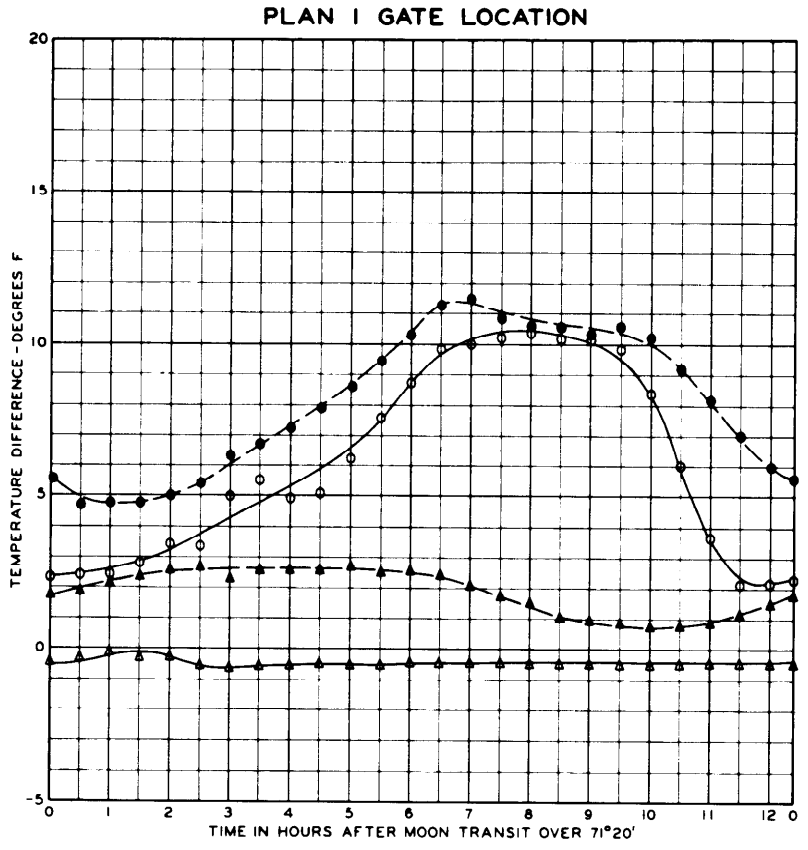


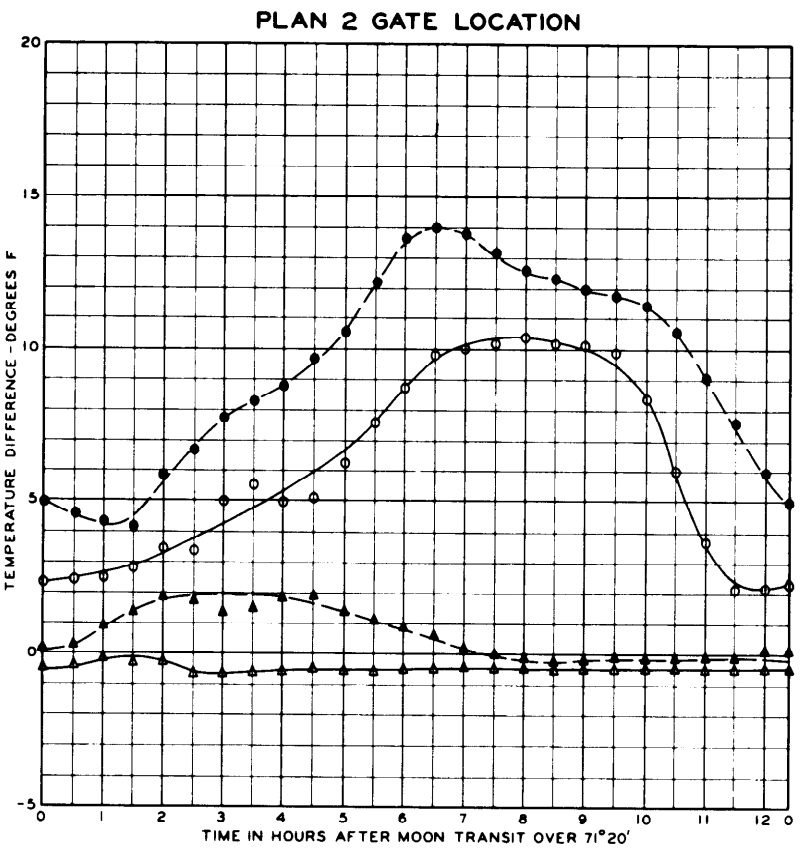
EFFECT OF FOX POINT BARRIER ON WATER TEMPERATURES

PLANS 1 AND 2

STATION G

Plate 6





LEGEND

SURFACE } BASE
INTAKE }

SURFACE } PLAN
INTAKE }

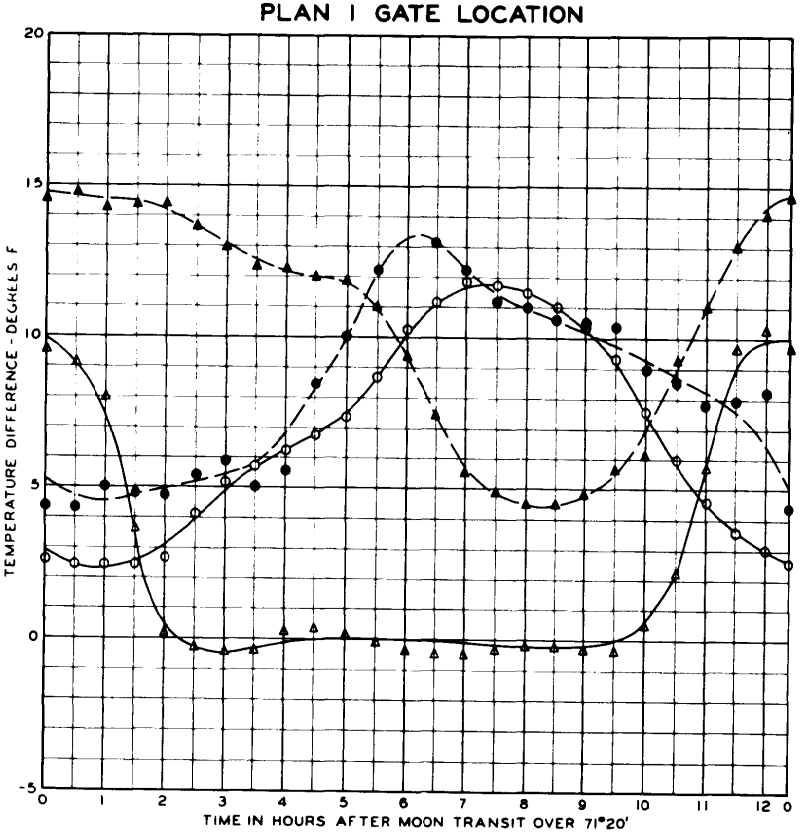
NOTE: DATA OBTAINED AFTER TEMPERATURES AT LOCATIONS B AND G WERE OBSERVED TO BE STABLE.

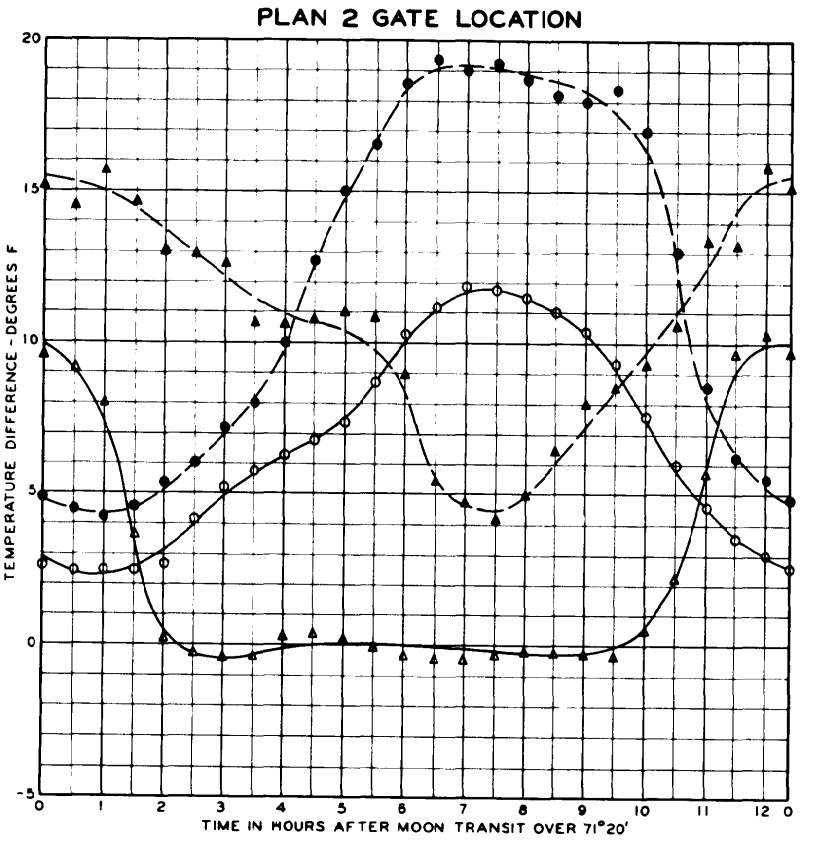
EFFECT OF FOX POINT BARRIER ON WATER TEMPERATURES THROUGHOUT A TIDAL CYCLE

PLANS 1 AND 2

SOUTH STREET INTAKE

Plate 7





LEGEND

SURFACE } BASE
INTAKE }

SURFACE } PLAN
INTAKE }

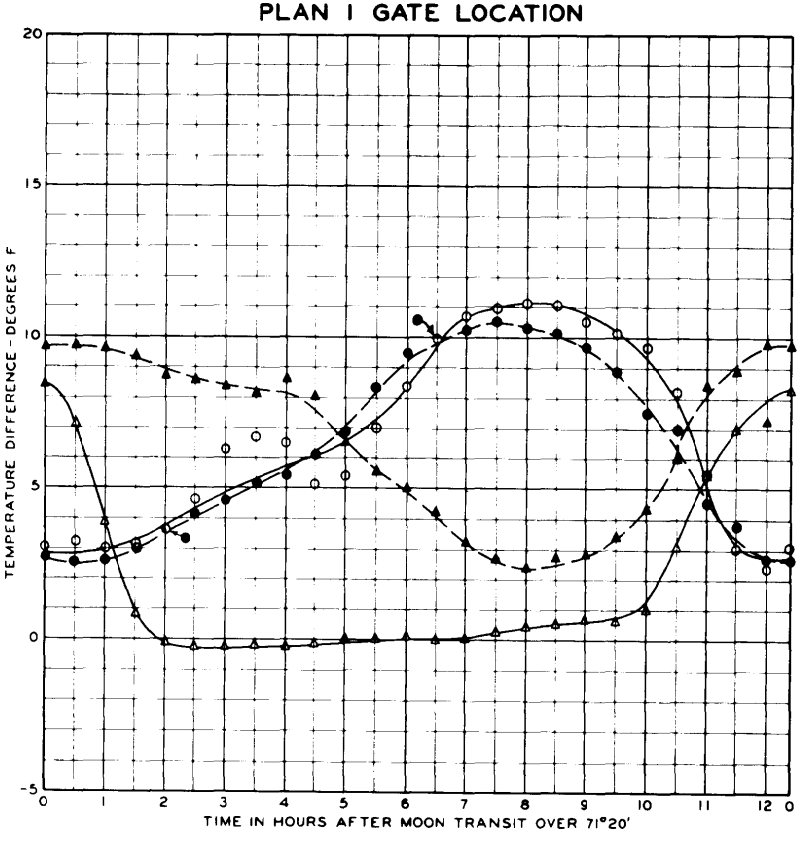
NOTE: DATA OBTAINED AFTER TEMPERATURES AT LOCATIONS B AND G WERE OBSERVED TO BE STABLE

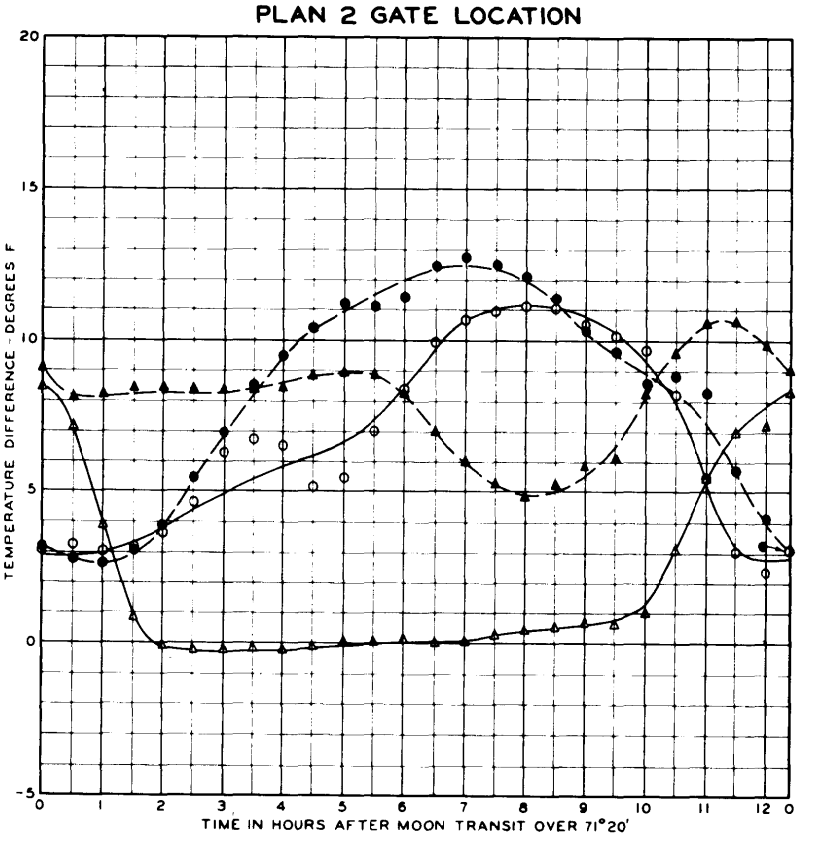
EFFECT OF FOX POINT BARRIER ON WATER TEMPERATURES THROUGHOUT A TIDAL CYCLE

PLANS 1 AND 2

MANCHESTER STREET INTAKE

Plate 8





LEGEND

SURFACE } BASE
BOTTOM }

SURFACE } PLAN
BOTTOM }

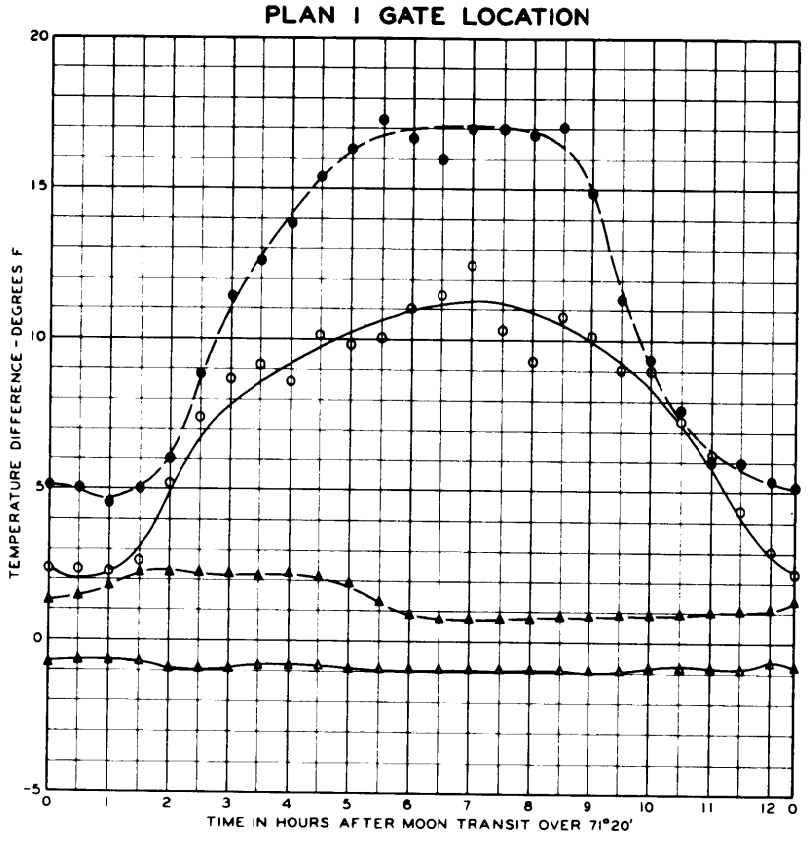
NOTE: DATA OBTAINED AFTER TEMPERATURES AT LOCATIONS B AND G WERE OBSERVED TO BE STABLE.

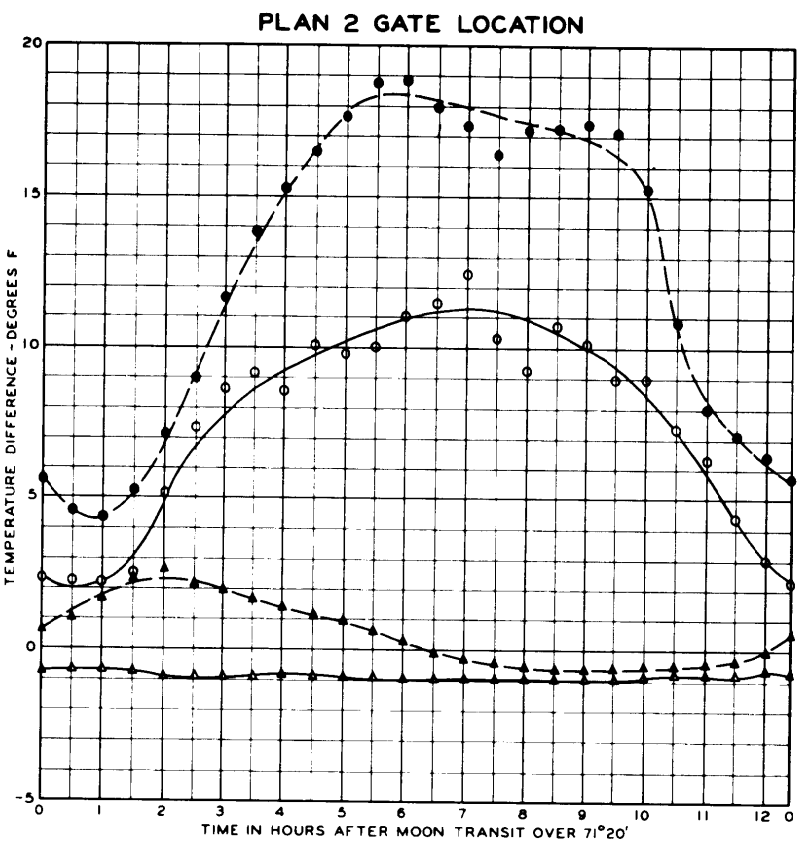
EFFECT OF FOX POINT BARRIER ON WATER TEMPERATURES THROUGHOUT A TIDAL CYCLE

PLANS 1 AND 2

STATION A

Plate 9





LEGEND

SURFACE } BASE
BOTTOM }

SURFACE } PLAN
BOTTOM }

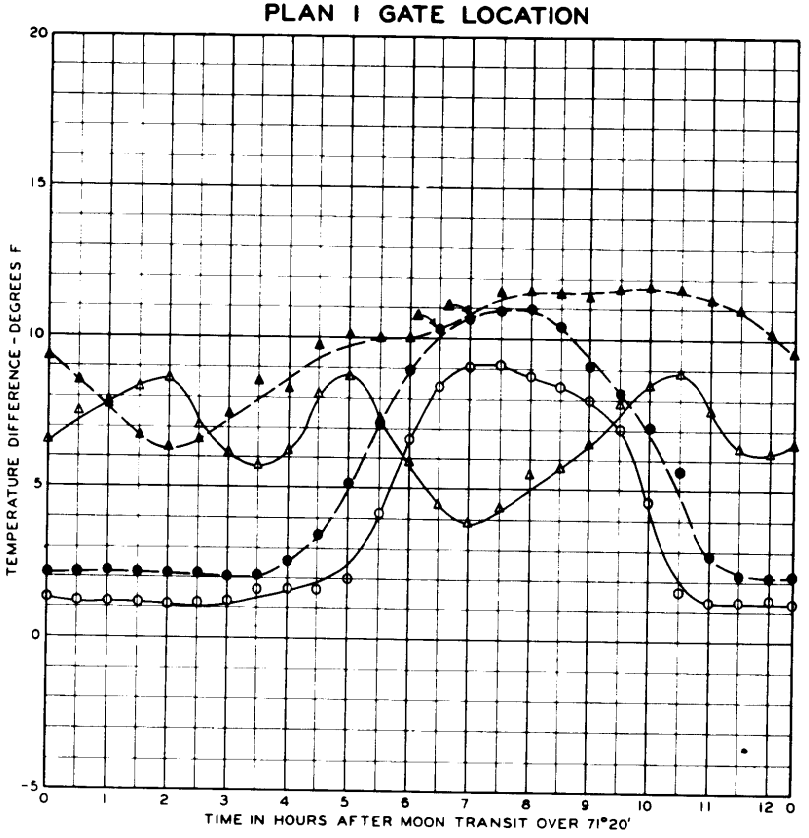
NOTE: DATA OBTAINED AFTER TEMPERATURES AT LOCATIONS B AND G WERE OBSERVED TO BE STABLE.

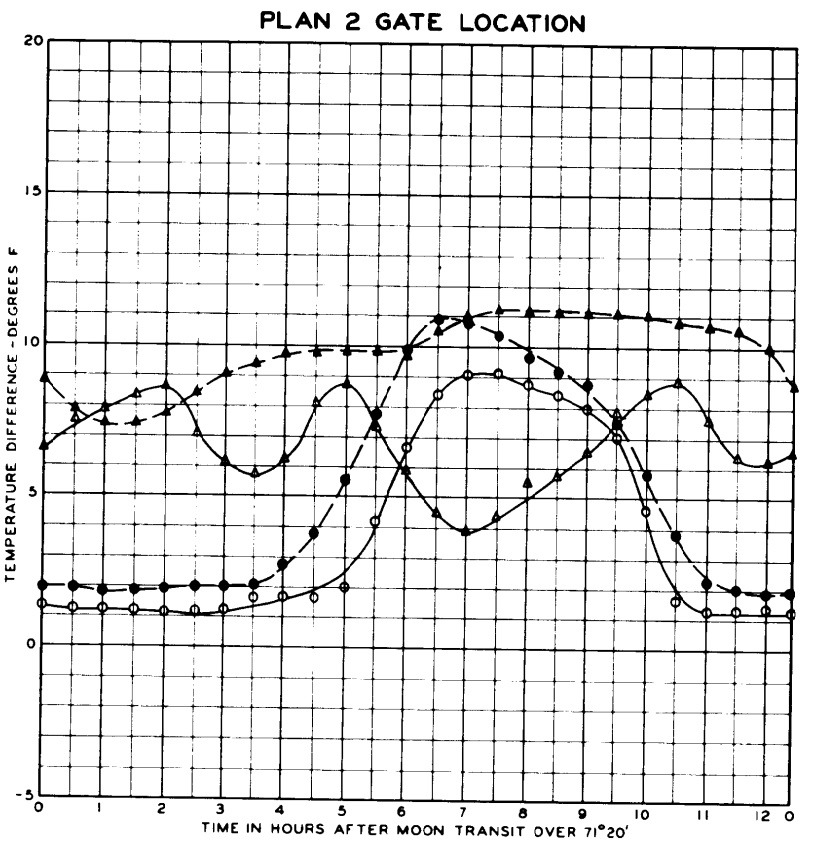
EFFECT OF FOX POINT BARRIER ON WATER TEMPERATURES THROUGHOUT A TIDAL CYCLE

PLANS 1 AND 2

STATION B

Plate 10





LEGEND

- SURFACE, BOTTOM } BASE
- SURFACE, BOTTOM } PLAN

NOTE: DATA OBTAINED AFTER TEMPERATURES AT LOCATIONS B AND G WERE OBSERVED TO BE STABLE.

EFFECT OF FOX POINT BARRIER ON WATER TEMPERATURES THROUGHOUT A TIDAL CYCLE

PLANS 1 AND 2

STATION G

Plate 11

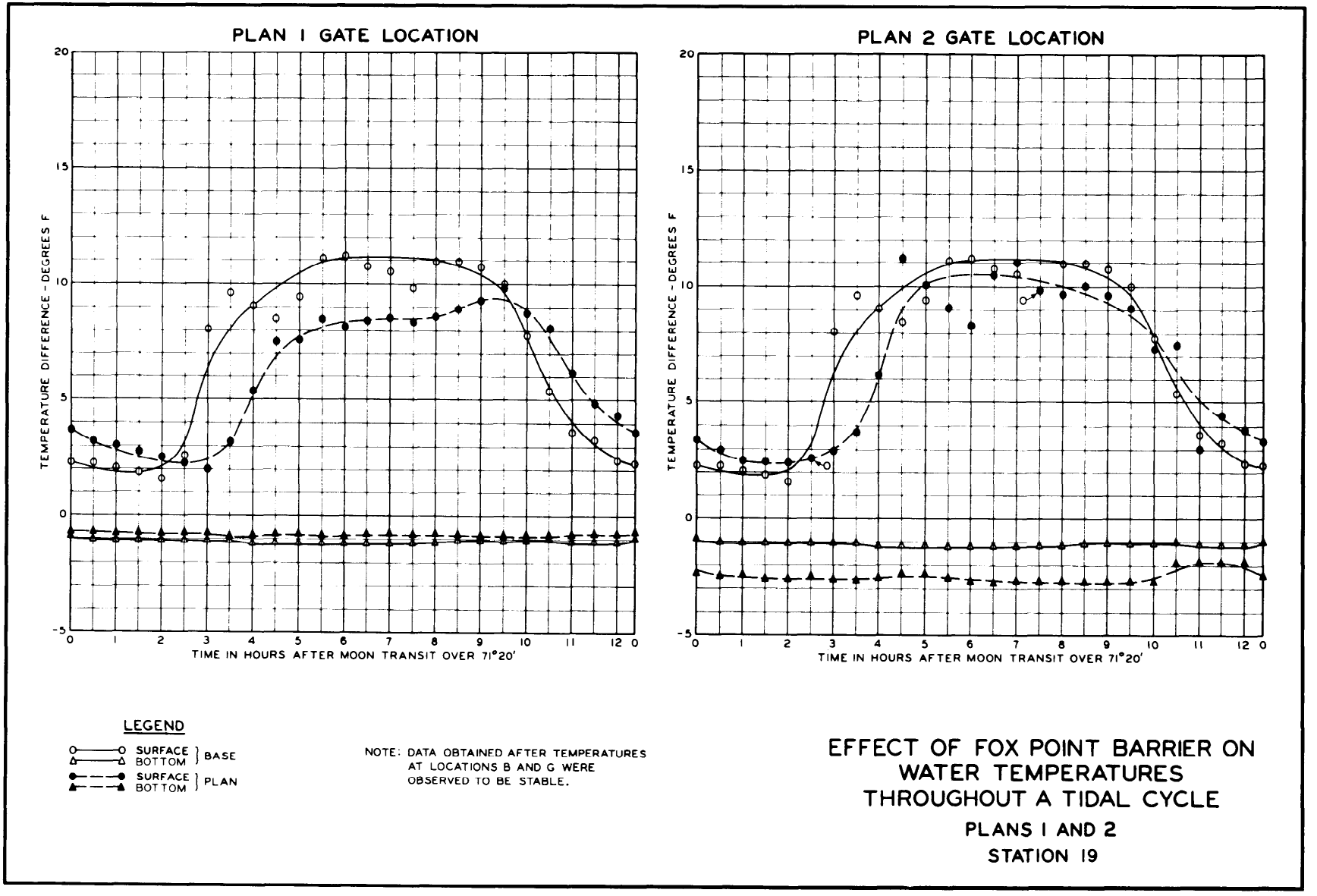

PLAN 1 GATE LOCATION
PLAN 2 GATE LOCATION
TEMPERATURE DIFFERENCE - DEGREES F
TIME IN HOURS AFTER MOON TRANSIT OVER 71°20'
LEGEND
SURFACE } BASE
BOTTOM }
SURFACE } PLAN
BOTTOM }
NOTE: DATA OBTAINED AFTER TEMPERATURES AT LOCATIONS B AND G WERE OBSERVED TO BE STABLE.
EFFECT OF FOX POINT BARRIER ON WATER TEMPERATURES THROUGHOUT A TIDAL CYCLE
PLANS 1 AND 2
STATION 19

Plate 12